Electromagnetic Sounding in the Columbia Basin, Yakima, Washington

M. J. Wilt, H. F. Morrison, K. H. Lee, and N. E. Goldstein, Lawrence Berkeley Lab

Summary

A controlled source electromagnetic survey was conducted near Yakima, Washington to map the thickness and resistivity of a thick surface volcanic sequence and the underlying sediments and infer structure based on the electrical interpretation. Field data were collected with the LBL EM-60 frequency domain system principally along a single 30 km long profile orthogonal to the regional strike direction. The data were initially interpreted by fitting the field results to layered models. We then pieced together these models to make a pseudo resistivity cross-section and based our geologic interpretation on this profile. At the southern end of the profile a deep well was available for comparison with the EM results. A smoothed version of the deep induction resistivity well log compared favorably to the averaged layered model obtained from the the EM soundings. The soundings yielded a three layer model corresponding to a thin low resistivity surface alluvial layer, 1.5 km thick high resistivity volcanic sequence and a basal low resistivity sedimentary sequence with resistivity increasing with depth. The pieced together resistivity section for the 30 km profile shows smoothly varying structure with the configuration of the volcanic and underlying sedimentary layer approximately concordant with topography. The most pronounced feature in an assymmetrical anticline beneath Boylston ridge at the eastern portion of the profile. This feature may indicate a potential trap for oil or gas.

Because of the unknown influences of topography and surface inhomogeneities we applied scale modeling to calculate the fields for an anticline model and for a model of a surface inhomogeneity; this calculated data was then compared to the field results. Scale modeling was performed with a system developed at U. C. Berkeley that uses off-the-shelf electronic components and metal for the modeling material. Measurements were made using fixed loop-variable receiver, central-loop and fixed separation configurations. The scale model data was then fit to layered models using a least-squares inversion code and pieced together models were compared to the field profiles.

Results indicate that the anticlinal structure could be detected by all of the arrays tested, but none could give an accurate representation using pieced together 1-d models. Of the methods tested the central-loop provided the best image of the structure but the fixed loop-variable offset system also provided reasonable estimates and this system is more practical for deep exploration. Results for the surface inhomogeneity model show that this shallow surface feature does not have a significant impact in determining the depth to the base of the surface volcanic layer except for stations at the edge of the structure.

Introduction

Under a 1983 agreement between Shell Oil Research and Development and Lawrence Berkeley Laboratory, a controlled source frequency domain electromagnetic sounding survey (CSEM) was made in an area between Ellensburg and Yakima, Washington. The primary purpose of the survey was to map the thickness and resistivity of the Columbia River Basalt volcanic sequence and to infer geologic structure from the electrical interpretation. We also wished to assess the potential of CSEM for mapping the thickness of the underlying sedimentary sequence beneath the volcanics.

General Geology

The site chosen for the EM survey lies within the Columbia Basin physiographic province. This region is known for the thick accumulations of Miocene basalt flows (the Columbia River Basalt Group or CRBG). Gravity and seismic refraction evidence indicates that volcanic sequence is up to 6 km thick near the center of the basin and is typically about 2 km thick elsewhere (Curry, 1984; Gresens and Stewart, 1981).

Figure 1 is a simplified lithologic log from Shell-Yakima YM 1-33, a 5,000 m wildcat drilled in 1981. The upper 1.5 km are composed of several separate flows of CRBG. Individual flow units are estimated to contain as much as 500 km^3 of material, and all have similar compositions and textures. Underlying the basalts are sedimentary rocks of the Oligocene Wenatchee Formation. These are chiefly mudstones and siltstones with minor sandstone beds. Although 500-m thick in YM 1-33, this formation is thought to reach thicknesses of around 1 km towards the center of the basin, and is the main hydrocarbon target in the basin. Underlying the Wenatchee is the Eocene Chumstick-Roslyn Formation. The upper and lower members of this formation are largely volcanic tuffs. A middle sandstone member contains thick coal beds and gave extensive gas shows in well YM 1-33.

Of principal interest in the search for petroleum in this region is the mapping of structure in the Wenatchee and Chumstick Formations. Although it is uncertain whether petroleum is trapped stratigraphically or by anticlines or faults, the first task is to search for structural traps. On the hypothesis that existing ridges and valleys are concordant with structures, the EM survey was designed to determine whether anticlines are concordant with ridges.

Results

Field measurements were made with the frequency-domain EM-60 system developed at Lawrence Berkeley Laboratory and used for several years in geothermal and crustal research (Morrison et al., 1978, Wilt et al., 1983). The Yakima-Boylston EM soundings were essentially measured along one 30 km-long northeast-southwest profile trending. About 80 percent of the stations were located directly on the profile; the other stations were located off-line to assess the continuity of the cross-section and to obtain resistivity sections beneath the transmitter sites.

A number of CSEM soundings were located near well YM 1-33. Resistivity sections obtained for these data were compared to the deep induction log from the well to evaluate the accuracy of the 1-D inversions. Figure 2 shows a highly smoothed induction resistivity log for the well together with an average resistivity section derived from EM soundings around the well. In general, there is an excellent agreement between the well log resistivity and the resistivity section obtained from CSEM sounding. Both data show three distinct horizons, a high resistivity unit extending from the surface to a depth of about 1 km, a layer of intermediate resistivity to about 1.5 km, and a deeper low resistivity section to more than 4.5 km. The smooth resistivity log does not give a clear indication on the boundary between the Wenatchee and Chumstick Formations. It shows only that the resistivity of the deeper horizons is slightly greater.

An interpreted resistivity versus depth cross-section for Profile A-A' is shown in Figure 3. The section was constructed using a plotting convention in which the layered-model parameters for each station are plotted at a point halfway between the source and receiver. At the bottom of the cross-section a plot of the magnitude of the ratio of the tangential to the radial field $|H_\theta|/|H_R|$ (T_h) is given. This parameter serves as a crude indicator of the effect of three-dimensional complexities (e.g., surficial inhomogeneities) on the data. For a layered earth the tangential field is zero, and the radial field is a purely secondary (induced) field. The ratio of these fields, therefore, indicates a departure from 1-D earth conditions, and anomalously high ratios may indicate current channeling due to the presence of conductive inhomogeneities or large-scale structure.

In general, the cross-section shows a remarkable consistency from sounding to sounding. The CSEM soundings indicate the following layers: (1) a locally-present low-resistivity surface-layer 0 to 150 m thick, (2) a high-resistivity second-layer 1.2 to 2.0 km thick, (3) a low-resistivity third-layer at least 1.5 km thick, and (4) a deeper, higher-resistivity basal layer of undetermined thickness.

The low-resistivity surface-layer is present only in Badger Pocket and near Johnson Canyon. The resistivity varies between 15 and 80 ohm-m which is are typical values for recent alluvial and lacustrine deposits. This layer is important because it helps establish the position of the top of the volcanic layer which is necessary to determine its true thickness. The higher resistivity second "volcanic" layer is up to 2 km thick and varies in resistivity along the profile from 50 to more than 300 ohm-m, averaging about 200 ohm-m. This layer is believed to be the CRBG and variations in resistivity are probably indicative of the relative contribution of sedimentary interbeds in the section. At the eastern edge of Badger Pocket the resistivity of this layer is also fairly low (< 100 ohm-m) which may reflect a distortion due to the thin, discontinuous surface layer in Badger Pocket. The T_h parameter shows a maximum in this area which probably indicates some current channeling within the conductive surface layer. For the third (sedimentary) layer, the resistivity ranges from 2 to 10 ohm-m with the higher values associated with the larger offset soundings. As no distinct layering could be detected, the resistivity increase is probably gradational as it was in the logs for well Yakima 1-33. The thickness of this layer is not resolved by CSEM measurements as it extends to or beyond the limits of investigation.

In general, the electrical cross-section of Fig. 3 indicates smoothly varying structure. The configuration of the volcanic and underlying sedimentary units (the V-S contact) seem more or less concordant with topography. Both the land surface and the V-S contact seem to dip at a shallow angle from northeast to southwest.

The most pronounced structural feature on the profile is an asymmetric anticlinal upwarp in the V-S contact beneath Boylston Ridge. Because the surface topography has a concordant upwarp, it appears that Boylston Ridge represents the surface expression of a simple post-CRBG fold. At the eastern edge of Badger Pocket we observe a flexure in the V-S contact which may be an artifact of 1-D inversions near the edge of a discontinuous surface conductor. Evidence for a distortion in current flow is also given by an increase in the T_h parameter plotted at the bottom of Figure 3.

Two-Dimensional Modeling

Because of the unknown effects of topography and the presence of surficial conductive sediments we were unsure of the accuracy of the 1-D inversions. Of particular interest is the upwarp in the sedimentary layer beneath Boylston ridge. This important structure lies beneath a topographic high and adjacent to a wedge of conductive sediments in Badger pocket. One test of the interpretation is to model the surface conductive feature and the two-dimensional upwarp in the sediments and compare these result to the field data. This allows us to assess the relative contributions of the surface structure and deep two-dimensional upwarp on the data to determine if our pieced-together model is appropriate.

Two-dimensional modeling is done using an analog (scale) model system developed at U.C. Berkeley (Wilt et al., 1986). The two dimensional models are shown schematically in Fig. 4. Three types of arrays were used in scale model measurements; (1) a fixed-loop array where the transmitter remains fixed and receiver stations are at various distances away, (2) a fixed-separation array where the transmitter-receiver separation is fixed and the pair move in tandem across the model, and (3) the central-loop array where the receiver is located at the center of the loop and the loop is moved across the model. For each model the scale model soundings were individually fit to layered models and these models were pieced together into cross-sections in a similar fashion to the field results.

For the anticline model , Fig. 4a, we are attempting to map the upper surface of an upwarp in the sedimentary section beneath a surficial volcanic layer. We present the inversion results for the fixed-loop system in Figure 5. This system is similar to the field configuration used in the Boylston-Yakima CSEM survey. The pieced-together 1-D inversions for this model give a good approximation to the structure although the interpreted structure appears broader than the true structure, and the resistivity of the upper layer is underestimated. One problem with the fixed-loop soundings is that the contribution from the anticline structure varies with the transmitter-receiver separation as well as the transmitter position so that the success in using 1-D inversions may be dependent on the particular array as well as the target.

All of the arrays tested could detect the anticlinal structure, but none gave an accurate representation of the structure based on 1-D inversions. The best estimate of the dimensions of the structure from 1-D inversions was made using the central-loop system. This array is not a practical one to use in deep sounding applications, however, because the transmitter loops must be quite large and only one sounding is made for each transmitter position. For deep exploration the most practical of the systems examined is the fixed-loop variable-offset system.

The next model we consider is the surface inhomogeneity (Fig. 4b). In this case we would like to see if such a surface feature could cause a pieced-together one dimensional interpretation to place a fictitious upwarp in a conducting basement. The model consists of a 45 ohm-m patch 100 meters thick, imbedded in a 200 ohm-m surface layer. At the base of the resistive layer is a flat lying 10 ohm-m layer. The results of pieced-together one dimensional inversions show that, in general, the surface feature does not seem to have a large effect on the interpretation. The depth to the conductive basement is well determined except for stations at the edge of the surface conductor. For receiver stations located immediately within the inhomogeneity the inversions slightly underestimate the depth to the conductive layer and stations just outside of the body seem to slightly overestimate this depth. This is a similar result to the interpretation of the field data near Badger Pocket. The resistivity of the top layer for stations located within the inhomogeneity is underestimated somewhat but the distortion does not seem to cause significant errors in the determination of the thickness of this layer.

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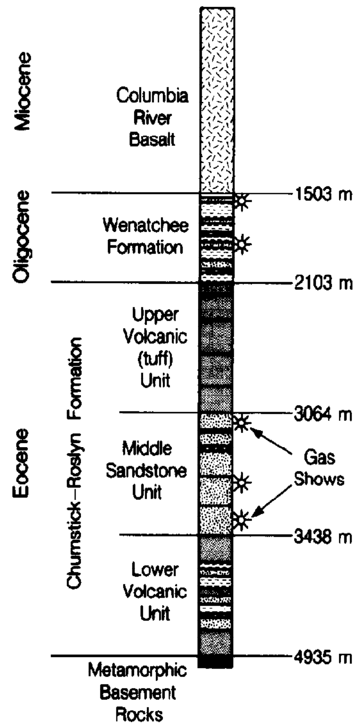

FIG. 1. Simplified geologic column from well Shell YM 1-33.

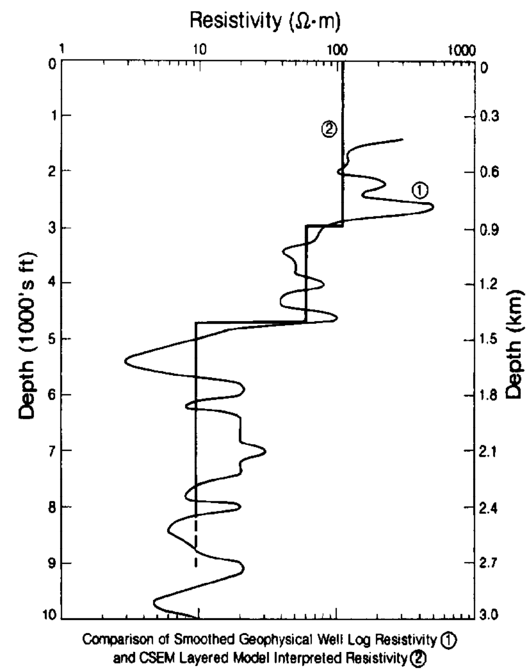

FIG. 2. Comparison of (1) the smoothed EM induction well log from well YM 1-33 and (2) layered model inversions for soundings taken near the well.

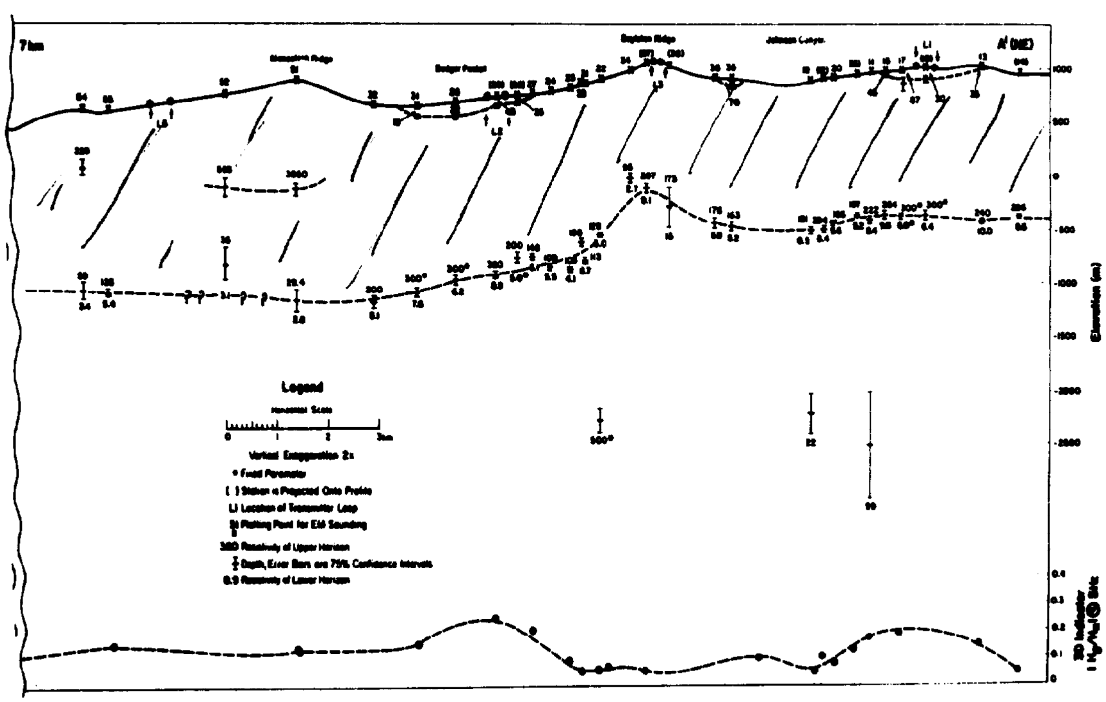

FIG. 3. Profile of pieced-together layered model inversions for profile A-A.

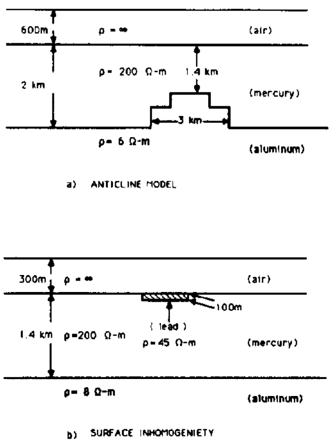

FIG. 4. Representation of the two-dimensional models for the (a) anticline (b) surface inhomogeneity and (c) buried valley studies.

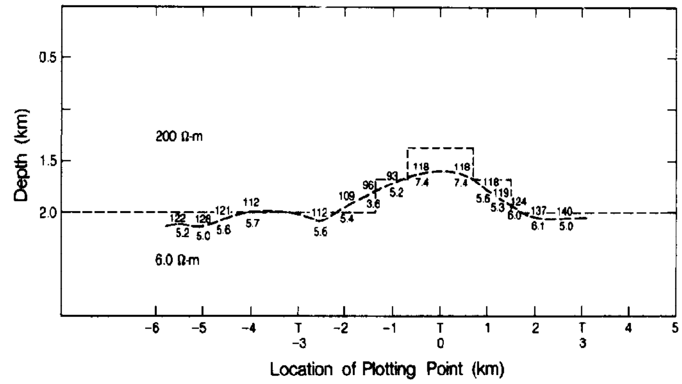

FIG. 5. Layered model inversion results for the fixed-loop variable-offset system. Results are plotted halfway between the source and receiver.